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ABSTRACT:

Earphone apparatus for use in an active noise reduction system comprises an assembly including a shell (14) accommodating first (11) and second (17) closely adjacent electroacoustical transducers. The shape and size of the shell (14) allows the shell (14) and first (11) and second (17) electroacoustical transducers to fit inside the concha of the ear.

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(54) Earphoning.

(57) Earphone apparatus for use in an active noise reduction system comprises an assembly including a shell (14) accommodating first (11) and second (17) closely adjacent electroacoustical transducers. The shape and size of the shell (14) allows the shell (14) and first (11) and second (17) electroacoustical transducers to fit inside the concha of the ear.

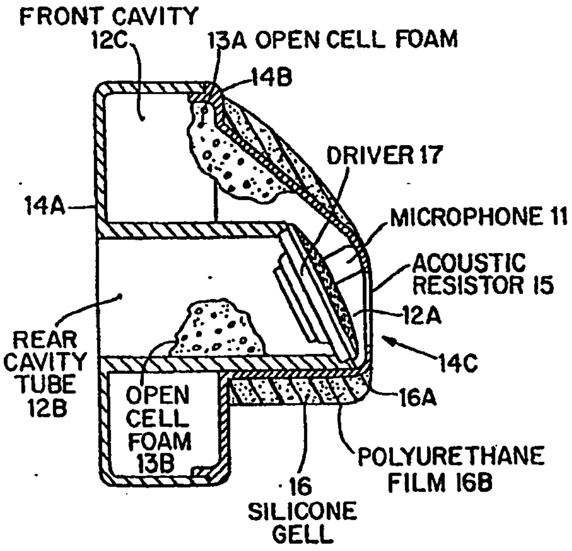

Fig 2

EP 0 425 129 A2

EARPHONING

The present invention relates in general to earphoning and more particularly concerns novel apparatus and techniques for actively reducing noise in earphones of especially lightweight compact structure.

For background reference is made to U. S. Patent Nos. 4,644,581 and 4,455,675 and copending U. S. application Serial No. 07/138,095.

According to those inventions, there is a headphone cavity and electroacoustical transducer, such as a pressure sensitive microphone, within the cavity for providing a signal corresponding to the sum of external noise and the sound produced by a headphone driver in the same cavity. A combiner combines this transduced signal with the input signal desired to be reproduced to produce an error signal representative of the noise and other differences between the input signal to be reproduced and the output of the headphone driver in the cavity. A servo comprising the combiner includes a compensator that compensates for these error signals to produce an output acoustical signal at the ear with external noise and distortion significantly reduced and with substantially uniform frequency response between the input to which the signal desired to be reproduced is applied and the ear.

It is an important object of this invention to provide an improved earphone in an active noise reducing system that is lightweight, compact and comfortable.

According to the invention, there is an assembly including a first electroacoustical transducer for transducing electroacoustical energy into an electrical signal and a second electroacoustical transducer closely adjacent to the first electroacoustical transducer for transducing electrical energy into acoustical energy in a shell small enough to be placed inside the concha of the ear. According to one aspect of the invention the shell is formed to fit inside a number of ear conchae. According to another aspect of the invention, the shell is custom molded to fit inside the concha of an individual user. According to another aspect of the invention, the second electroacoustical transducer at least in part is on the boundary between an inside or front cavity closer to the inner ear than an outside or rear cavity further from the inner ear. The first electroacoustical transducer is located inside the front cavity close to the second electroacoustical transducer. The first electroacoustical transducer is typically a microphone having a microphone diaphragm perpendicular to the driver diaphragm of the second electroacoustical transducer, typically an earphone driver preferably heavily damped. According to another aspect of the invention the shell is formed with an inside opening facing the second electroacoustic transducer and covered by acoustically resistive material, such as fine wire mesh. According to another aspect of the invention, the rear cavity is a tube coaxially surrounded at least in part by a portion of the front or inside cavity with each of the cavities preferably largely filled with open cell foam. Preferably a layer of polyurethane film encloses a layer of silicone gel along a portion of the outside of the shell.

Numerous other features and advantages of the invention will become apparent from the following detailed description when read in connection with the accompanying drawing in which:

FIG. 1 is a block diagram illustrating a system embodying the invention;

FIG. 2 is an axial sectional view of an embodiment of the invention;

FIGS. 3 and 4 are equivalent electrical circuits characterizing the transfer function of a system according to the invention at high and low frequencies, respectively;

FIGS. 5A and 5B are graphical representations of the effect of the resistive screen on magnitude and phase responses, respectively, of the system;

FIG. 6 is an equivalent electrical circuit modeling passive transmission loss of the system;

FIG. 7 illustrates the effect of volume at the front or inner cavity and open back on the passive attenuation;

FIG. 8 illustrates the effect of the back cavity of two cc on driver efficiency;

FIG. 9 is a plan view showing elements of an embodiment of the invention in the left ear;

FIG. 9A is a view through section A-A of FIG. 9; and

FIG. 9B is a view through section B-B of FIG. 9;

With reference now to the drawings and more particularly FIG 1 thereof, there is shown a block diagram illustrating the logical arrangement of a system incorporating the invention corresponding substantially to FIG. 1 of the aforesaid '581 patent. A signal combiner 30 algebraically combines the signal desired to be reproduced by the earphone on input terminal 24 with a feedback signal provided by microphone preamplifier 35. Signal combiner 30 provides the combined signal to compressor 31 which limits the level of the high level signals. The output of compressor 31 is applied to compensator 31A. Compensator 31A includes compensation circuits to insure that the open loop gain meets the Nyquist stability criteria, so that the system will not oscillate when the loop is closed.

The system shown is duplicated once each for the left and right ears.

Power amplifier 31 amplifies the signal from compensator 31A and energizes earphone driver 17 to provide an acoustical signal in cavity 12 that is combined with an outside noise signal that enters cavity 12 from a region represented as acoustical input terminal 25 to produce a combined acoustic pressure signal in cavity 12 represented as a circle 36 to provide a combined acoustic pressure signal applied to and transduced by microphone 11. Microphone amplifier 35 amplifies the transduced signal and delivers it to signal combiner 30.

Referring to FIG. 2, there is shown a diametrical sectional view of an embodiment of the invention. Microphone 11 is shown positioned in front cavity 12A with driver 17, preferably heavily damped, located along the boundary between inner or front cavity 12A and outer or rear cavity 12B. Front or inner cavity 12A has a portion 12C coaxially surrounding rear or outer cavity 12B. Rear or outer cavity 12B and front cavity 12A including portions 12C are filled with open cell foam 13B and 13A, respectively. A shell 14 typically made of plastic includes a rear or outer portion 14A and front or inner portion 14B joined together with front or inner portion 14B formed with an opening 14C covered by acoustic resistive material 15, such as fine wire mesh. A cushion 16 is made of silicon gel 16A covered by polyurethane film 16B and is shaped to provide comfort and seal to different ears without moving microphone 11 away from the entrance to the ear canal. The rear or outer side of the diaphragm of driver 17 is exposed to the outside through rear or outer cavity 12B open at the outside as shown.

Having described structural arrangements certain principles of the invention will be described. The invention is relatively compact and lightweight while providing comfort to the wearer. Locating structure in the concha of the ear allows reduction of size and weight as compared with structures having large earcups and large circumaural cushions. The invention still provides significant noise attenuation.

An important aspect of the system is maintaining stability. The invention includes structure modifying the transfer function between driver 17 and microphone 11 so as to provide sufficient gain and phase margins. The transfer function depends not only on the transducers, but also the acoustics of the cavity in which the transducers are located and differs from one user to another having different concha characteristics. At high frequencies variations are caused by variation in human ear canals, volumes, sizes and eardrum impedances. The effect of these variations on the transfer function may be reduced by establishing a relatively large volume in the front or inner cavity 12A.

Referring to FIGS. 3 and 4, there are shown simplified equivalent electrical circuits characterizing the transfer function of the system at high and low frequencies, respectively. C_D is driver 17 compliance, M_D is driver 17 mass, C_F is compliance of front or inner cavity 12A, C_E is compliance of the ear canal cavity, and R_D is driver 17 resistance. If the front cavity volume is chosen to satisfy the condition $C_D > C_F > C_E$, then the transfer function can be approximated by:

$$\frac{V_O}{V_{IN}} \approx \frac{1}{S_2 M_D C_F + 1}$$

and is not a function of the ear canal compliance. (The average volume of an ear canal is about 2cc).

In FIG. 4 R_s is the resistance of acoustic resistance 15 and M_L represents mass of the leak between front cavity 12A and the concha. Without resistive screen 15, response of the system has a second order roll-off which causes 180° phase shift that would cause a stability problem. The problem could be overcome by electronic compensation at low frequencies; however, this approach would limit the dynamic range of the system. A preferred approach according to the invention is to place resistive element 15 in the opening 14C of shell 14B at the front or inner cavity 12A. The resistive element is preferably chosen with resistance low enough to so that it won't significantly effect cancellation.

Referring to FIGS. 5A and 5B, there are shown graphical representations of the effect of resistive screen 15 on amplitude and phase response, respectively, of the system showing the relatively slight attenuation introduced by the resistive screen with system responses being represented by the lower curves and the avoidance of the 180° phase shift.

An advantage of the invention is that by using a smaller driver 17 and by placing the sensing microphone 11 close to the entrance of the ear canal, the bandwidth of the active cancellation may be extended up to 1500 Hz, of the order of twice as high as practically available with a circumaural system disclosed in the aforesaid patents. Another feature of the invention is that it is characterized by a significant amount of passive attenuation at high frequencies to provide effective noise protection. Passive attenuation is a function of the leak and volume of the front or inner cavity. It was discovered that for a small structure, this volume preferably should not exceed more than about 10 cc. It was found that the preferred approach to passive attenuation is to use almost the entire available volume of the shell as a front cavity with none or negligible back cavity volume.

Referring to FIG. 6, there is shown an equivalent electrical circuit for passive transmission loss analysis. It was determined experimentally that even with a very good seal, the leak mass M_L dominates over driver impedance C_D, R_D, M_D, and the open back of the driver through rear cavity 12B does not deteriorate the system performance significantly.

Referring to FIG. 7, there is shown a graphical representation illustrating the negligible difference in passive attenuation when the front or inner cavity is large with closed or open back providing significantly better passive attenuation than using a small volume front or inner cavity with an open back.

A feature of the invention is the use of a very small driver 17 resulting in broader cancellation bandwidth in a small structure. Driver maximum power handling capability is typically related to the driver size, and the driver efficiency is typically related to the volume of the rear or outer cavity 12B. For higher output it is desirable to use no back or outer cavity at all. Referring to FIG. 8, there is shown a graphical representation showing the increased output without back cavity compared with the output with a rear or outer cavity of the order of 2 cc.

A preferred form of the invention comprises a shell structure having a custom fit piece for each ear. Referring to FIG. 9, there is shown a plan view of a form of the invention. FIGS. 9A and 9B show sectional views through section A-A and B-B of FIG. 9 illustrating the custom snap-on ear cavity mold 14D that snaps on shell 14 formed with an opening 14E at the entrance to the ear canal exposing acoustic resistance 15. Driver 17 and microphone 11 are oriented as shown with the diaphragm of driver 17 perpendicular to the concha axis. Custom ear cavity mold 14D may be fabricated in substantially the same manner as custom molds for hearing aids.

There has been described novel apparatus and techniques for providing compact lightweight earphones in a system that provides significant active noise cancellation. Other embodiments are within the claims.

Claims

1. Earphone apparatus for use in an active noise reduction system comprising: an assembly including a shell (14) accommodating first (11) and second (17) closely adjacent l ctroacoustical transducers of shape and size that allows the shell (14) and first (11) and second (17) electroacoustical transducers to fit inside the concha of the ear.

2. An apparatus according to claim 1, wherein the shell (14) is formed with front (12A,12C) and rear (12B) cavities.

3. An apparatus according to claim 2, wherein the first electroacoustic transducer is a microphone (11) in the front cavity (12A), and the second electroacoustic transducer is a driver (17) forming at least a portion of the boundary between the front (12A) and rear (12B) cavities.

4. An apparatus according to claim 2 or claim 3, wherein the front cavity (12C) at least partially coaxially surrounds the rear cavity (12B).

5. An apparatus according to any of claims 2 to 4, wherein the front cavity (12A) is formed with an opening (14C) covered by material (15) having acoustic resistance.

6. An apparatus according to any of claims 1 to 5, wherein the shell (14) is custom moulded to the concha of the wearer.

7. An apparatus according to claim 6, wherein the shell (14) includes a snap-on ear cavity mould (14D).

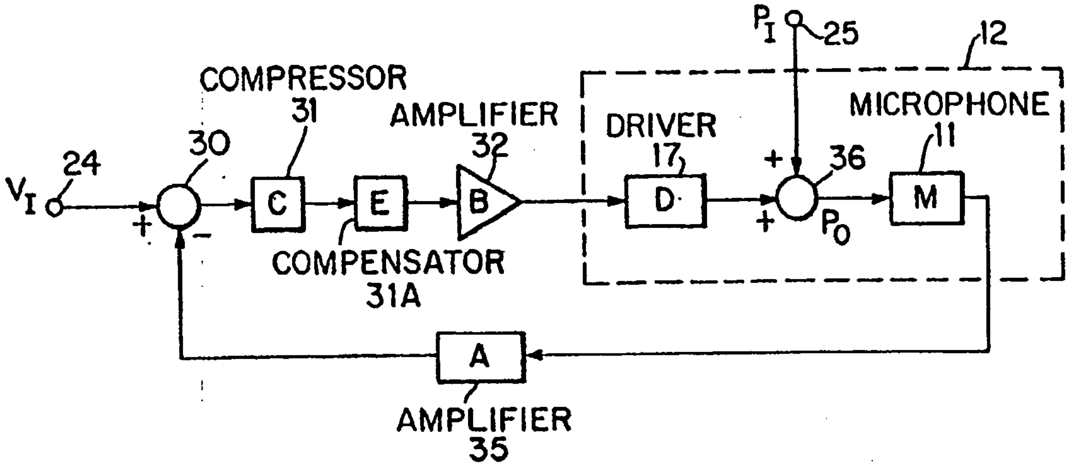
P
I
25
12
COMPRESSOR
31
AMPLIFIER
32
DRIVER
17
MICROPHONE
11
V
I
24
30
+
C
E
B
D
+
36
M
+
−
P
0
COMPENSATOR
31A
A
AMPLIFIER
35

Fig. 1

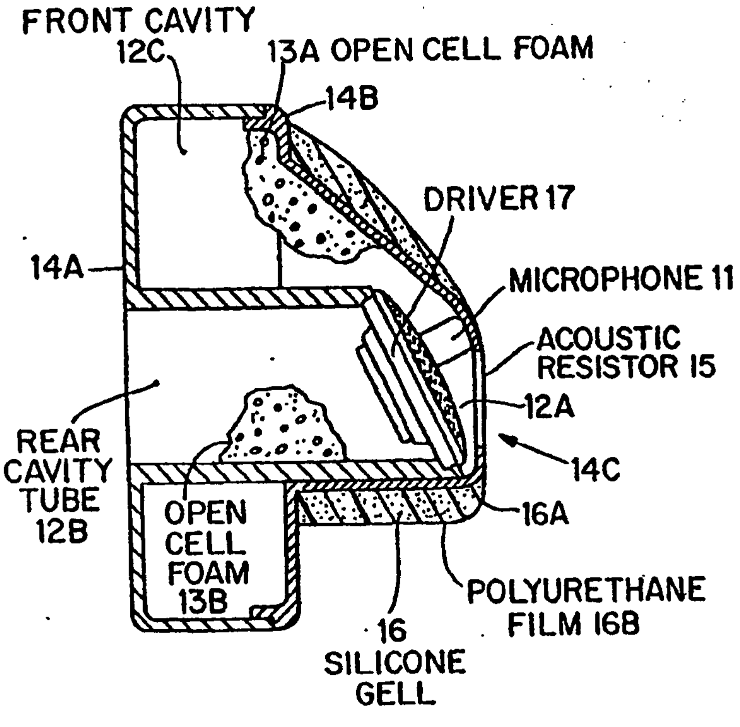
FRONT CAVITY
12C
13A OPEN CELL FOAM
14B
DRIVER 17
14A
MICROPHONE 11
ACOUSTIC
RESISTOR 15
12A
REAR
CAVITY
TUBE
12B
14C
OPEN
CELL
FOAM
13B
16A
POLYURETHANE
FILM 16B
16
SILICONE
GELL

Fig 2

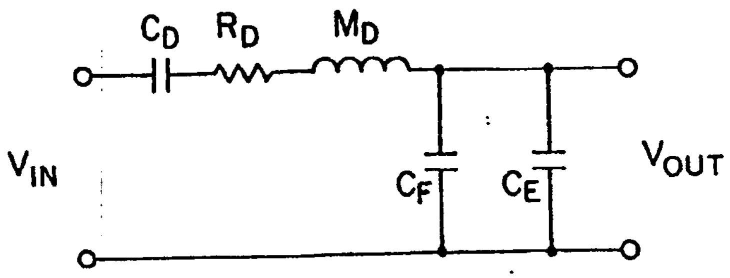

Fig. 3

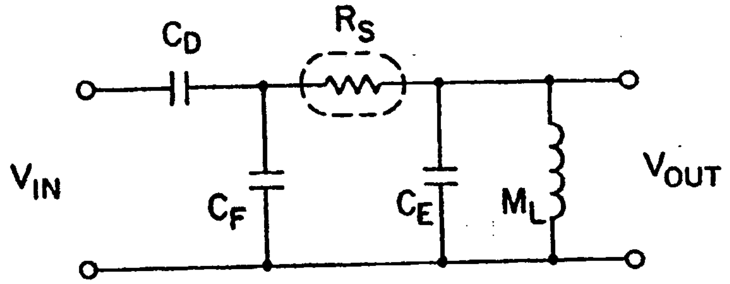

Fig. 4

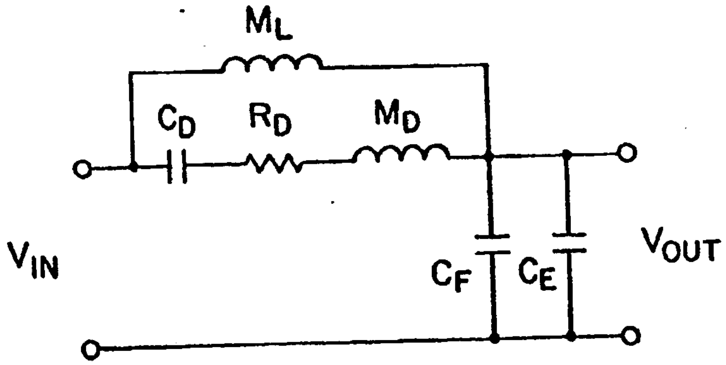

Fig. 6

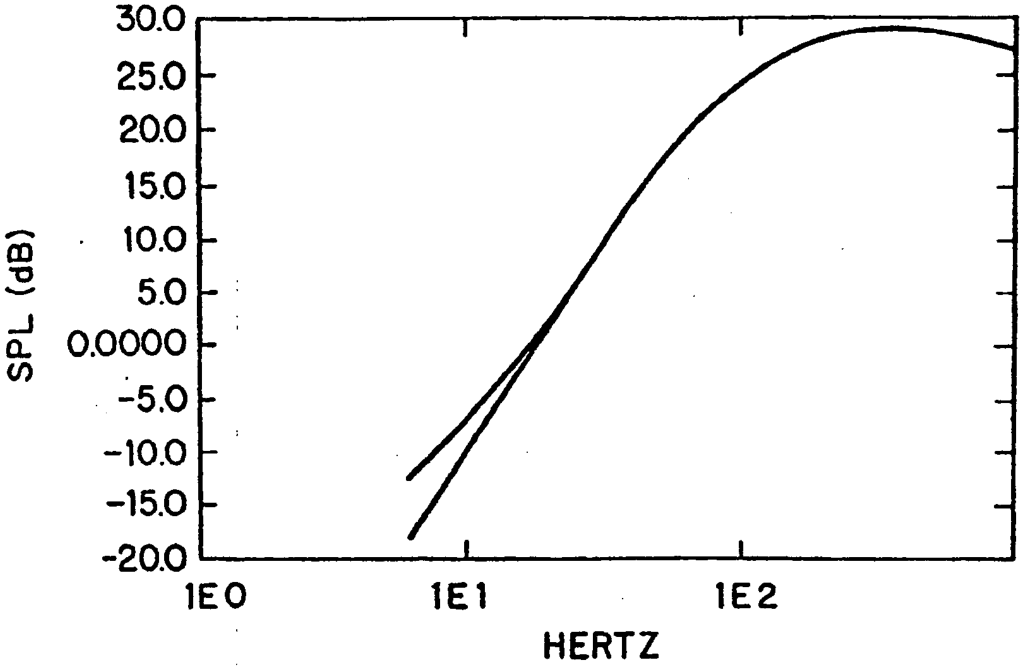
30.0
25.0
20.0
15.0
10.0
5.0
0.0000
-5.0
-10.0
-15.0
-20.0
SPL (dB)
1E0
1E1
1E2
HERTZ

Fig. 5A

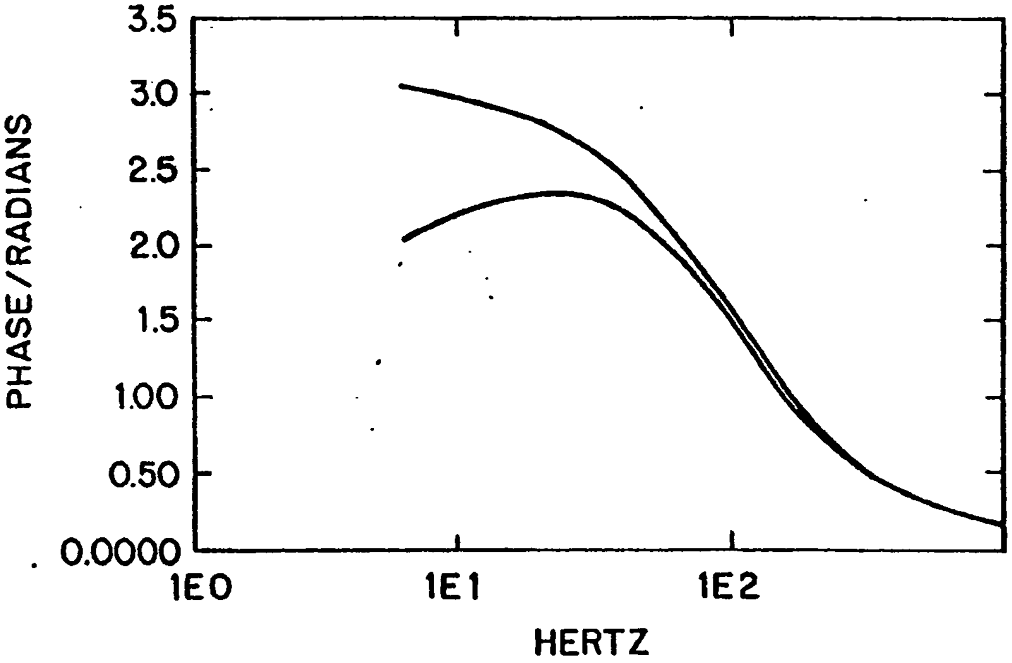
3.5
3.0
2.5
2.0
1.5
1.00
0.50
0.0000
PHASE/RADIANS
1E0
1E1
1E2
HERTZ

Fig. 5B

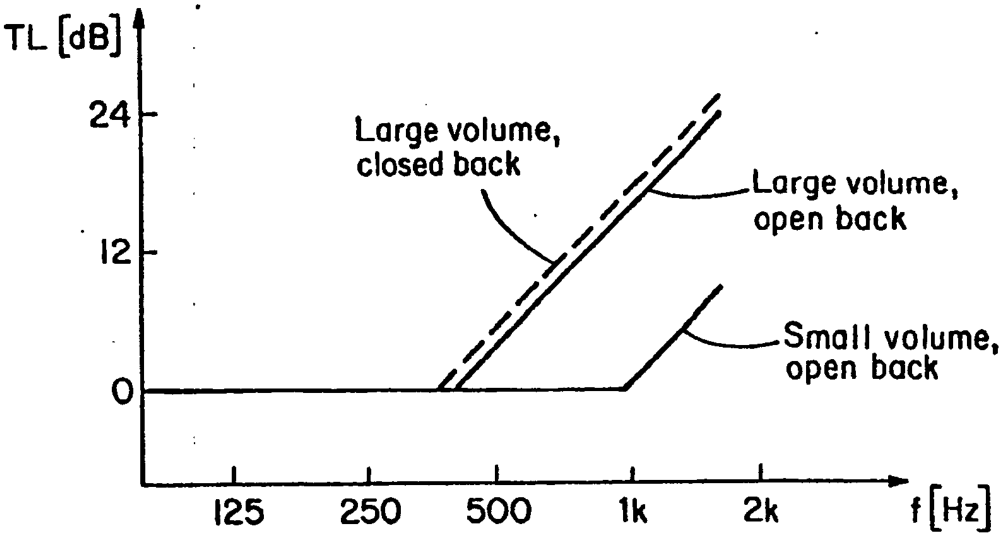
TL [dB]
24
12
0
Large volume, closed back
Large volume, open back
Small volume, open back
125
250
500
1k
2k
f [Hz]

Fig. 7

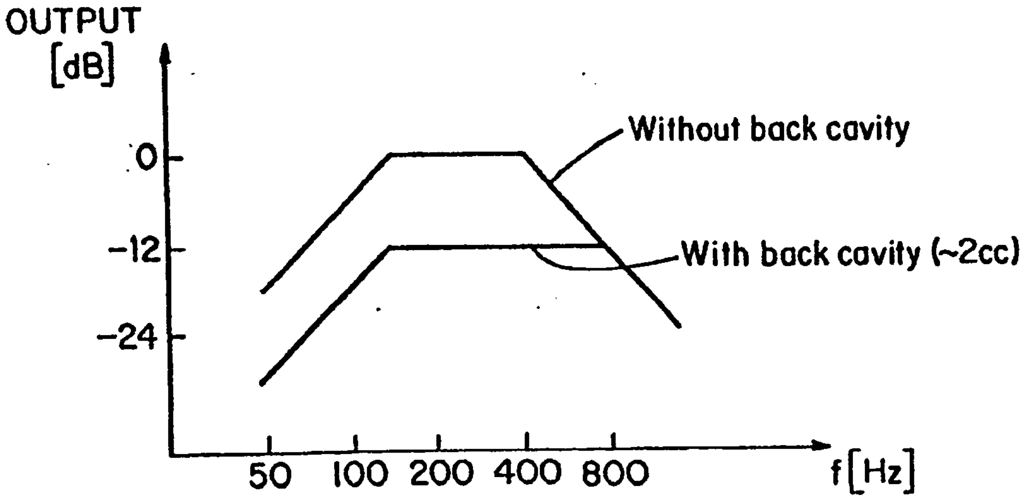
OUTPUT [dB]
0
-12
-24
Without back cavity
With back cavity (~2cc)
50
100
200
400
800
f [Hz]

Fig. 8

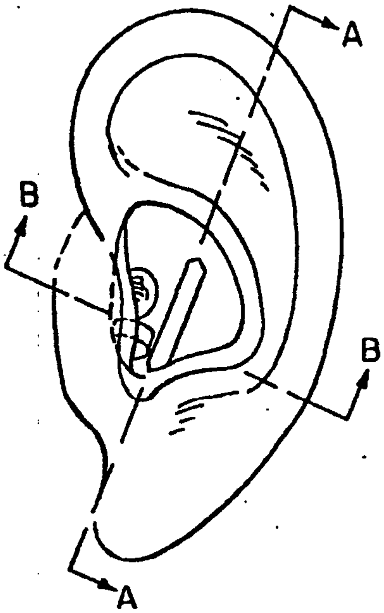

Fig. 9

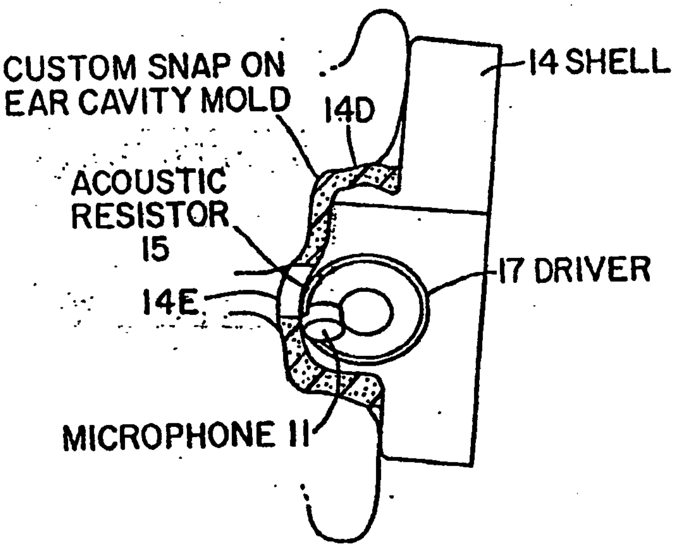

Fig. 9A

SECTION A-A

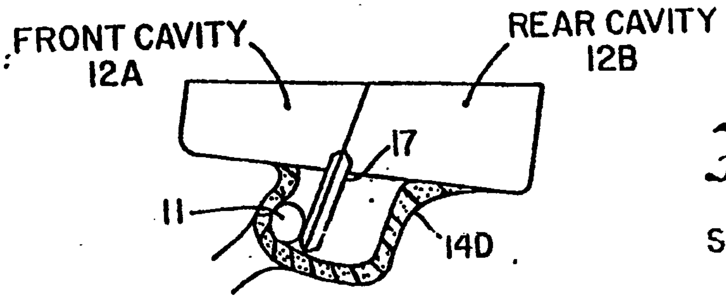

Fig. 9B

SECTION B-B